A CLASSIC EXAMPLE OF RAPID CYCLOGENESIS IN THE MIDWEST, FEBRUARY 25–28, 1958

HAROLD J. SHELLUM AND GORDON C. TAIT

National Weather Analysis Center, U. S. Weather Bureau, Washington, D. C.

1. INTRODUCTION

A severe storm developed over the central High Plains on February 25, 1958 and grew so rapidly that by February 26 the circulation around it encompassed almost all of the United States. As this rapidly cyclogenetic storm moved eastward, reaching its maximum intensity on February 27, it continued to dominate the weather over the eastern half of the United States. Many stations in Kansas and Oklahoma recorded their lowest sea level pressure on record as the storm crossed the Great Plains.

A very interesting analogue of this storm occurred on February 27, 1902. A weather map of this analogue storm appears in *Hydrometeorological Report* No. 2 [1]. Oklahoma City, Okla. had recorded its previous record low sea level pressure during the 1902 storm, exactly 56 years to the day earlier than the date of the new record set by the 1958 storm.

After briefly describing the weather, this paper reviews some of the synoptic and dynamic aspects of the rapid cyclogenesis, with particular emphasis given to the upper troposphere.

2. WEATHER

Sharp temperature changes, widespread precipitation in the form of heavy rain, snow, and glaze, plus high winds, tornadoes, and floods highlighted the life of the storm (See, for example, fig. 3A). At many stations in Kansas and Oklahoma passage of the Low resulted in the lowest pressure on record. On the night of February 26, 1958 four tornadoes in Mississippi caused 12 deaths and 80 injuries; although no large towns were hit property damage was believed to be near one million dollars. Snowfall ranging from 3 inches in northern Oklahoma to 17 inches at Pierre, S. Dak. was preceded by a belt of glaze in eastern Nebraska and South Dakota. Winds of 50 miles per hour or more caused heavy drifting of the snow, blocking roads in many sections of Kansas, Nebraska, and South Dakota. Blizzard conditions actually continued in many sections of South Dakota through March 2. Temperatures dropped sharply in the Far West on February 26. Frost and freezing occurred in nearly all sections of Washington and Oregon on February 28. For the week of February 24 through March 2, temperatures averaged as much as 6° F. below normal in the southwestern third of the country. Ahead of the storm temperatures were above normal with departures ranging up to 18 F.° or more in the upper Mississippi Valley. In the Southeast, this was the first mild week of the year [2].

General precipitation fell as the cold front associated with this storm moved across the Far West. On the Sacramento side of the Coast Range in California, rains totaling up to 8 inches or more made streams unusually high. Snow up to 5 feet was reported from some mountain areas of Utah.

On February 26, 27, and 28 moderate to heavy rains fell in the Middle and South Atlantic Coastal States and heavy rain fell in New England. One to two inches of rain plus snow melt caused some flooding in southeastern New England. High tides produced by 50-m. p. h. winds occurred along the southwestern Connecticut coast where 500 people were evacuated.

3. CYCLOGENESIS AND THE JET STREAM

Figure 1A shows the surface map at 1200 GMT February 25, 1958. At this time the main low pressure center was in southern Canada, just north of Montana. A cold front, which had been followed with good continuity all across the Pacific, became oriented through eastern Idaho southwestward through southern California. A well defined trough lay along this cold front, especially in the Rocky Mountain area; another trough lay to the lee of the Rockies. Figure 2A shows the surface map at 1200 GMT February 26. During this 24-hour period rapid cyclogenesis took place in the High Plains of Kansas and Nebraska. A Low with a central pressure of 978 mb. developed in western Kansas while the Low in southern Canada filled and moved rapidly northeastward. The Low in western Kansas occupied the same location where the 1008-mb. isobar lay 24 hours earlier (note position through western Kansas on fig. 1A), indicating a fall there of about 30 mb. Actually, most of the deepening took place between 1200 GMT February 25 and 0300 GMT February 26 when the first closed isobar around the Low appeared, centered near the intersection of the Colorado, Kansas, and Nebraska borders. During this 15-hour period most

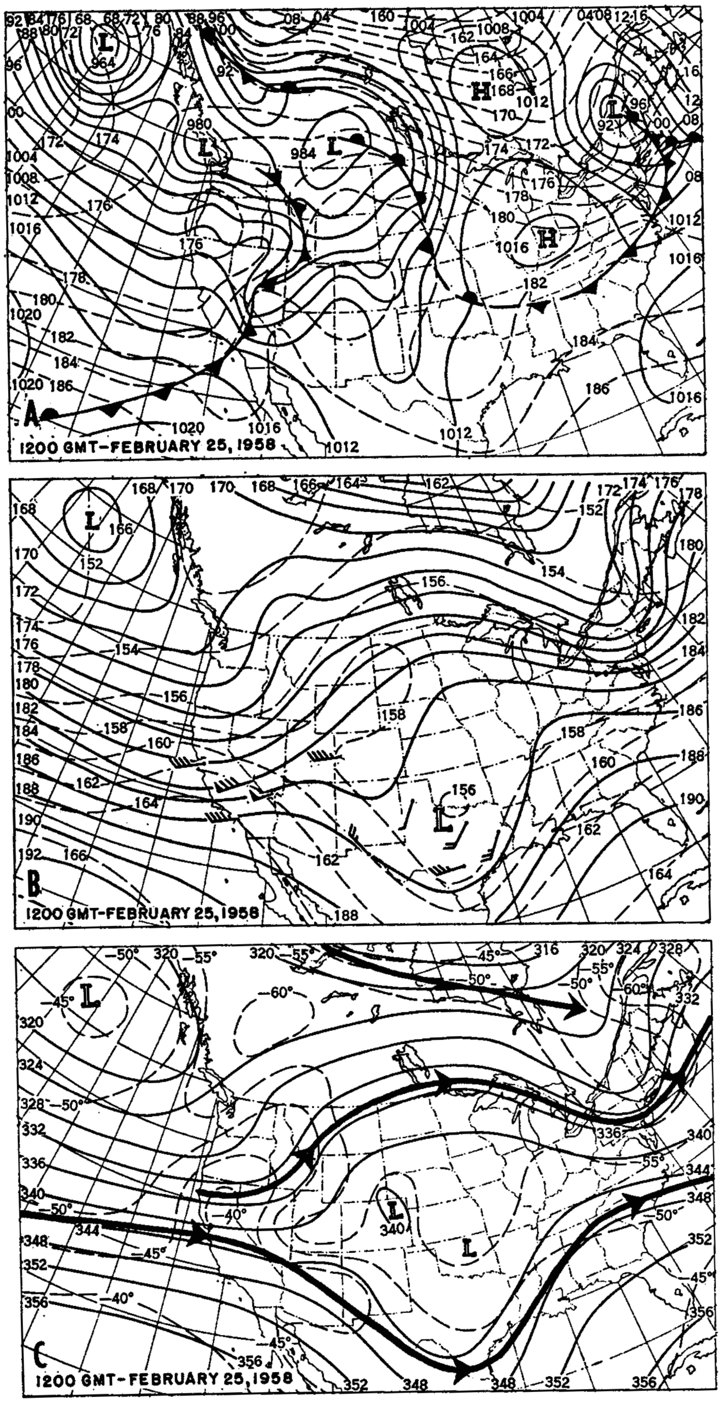

FIGURE 1.—1200 GMT charts February 25, 1958. (A) Surface weather map with isobars (solid lines) at 4-mb. intervals and 1000–500 mb. thickness contours (dashed lines) in hundreds of feet and at intervals of 200 ft. (B) 500-mb. contours (solid lines) and 500–250-mb. thickness contours (dashed lines) in hundreds of feet and at intervals of 200 ft. (C) 250-mb. contours (solid lines) in hundreds of feet and at 400-ft. intervals, the 250-mb. jet stream (heavy solid lines) with arrows showing the direction of flow, and 250-mb. isotherms (dashed lines) at intervals of 5° C.

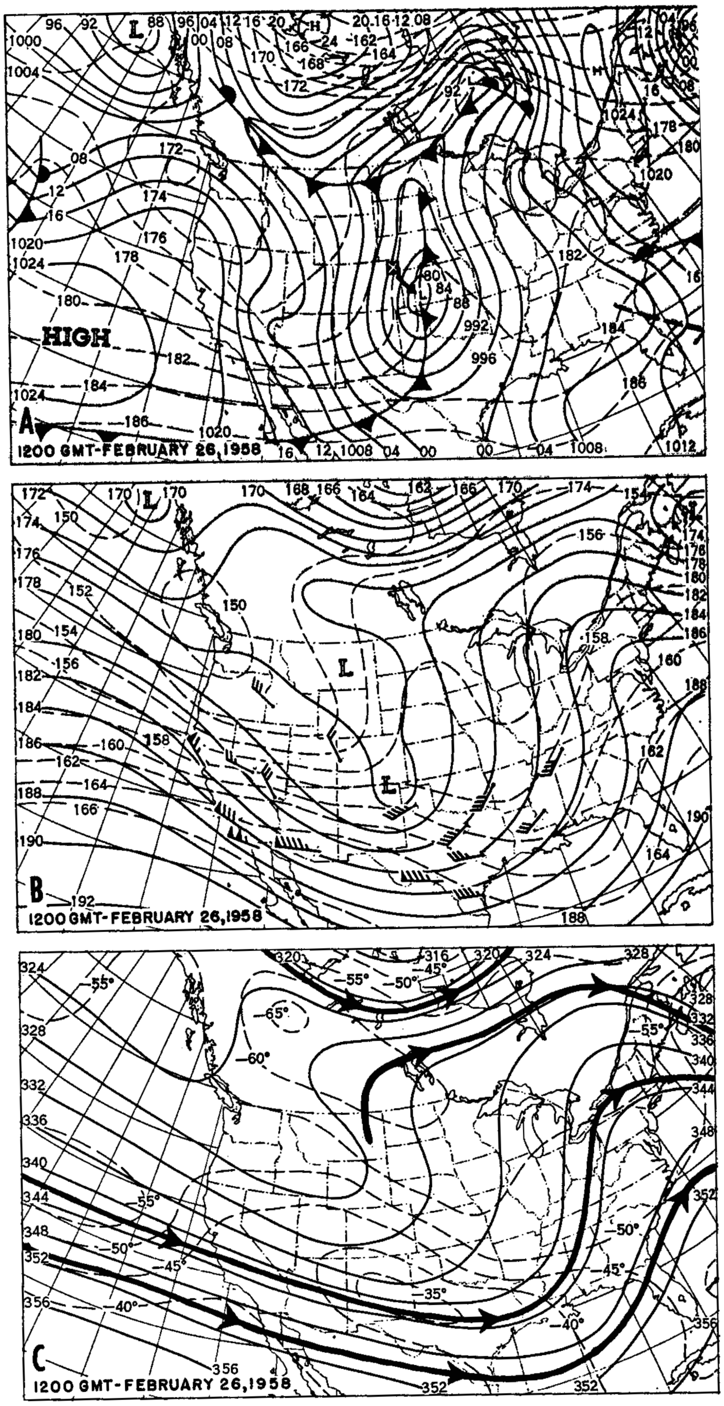

FIGURE 2.—1200 GMT charts, February 26, 1958. (A) Surface weather map with isobars (solid lines) at 4-mb. intervals and 1000–500-mb. thickness contours (dashed lines) in hundreds of feet and at intervals of 200 ft. (B) 500-mb. contours (solid lines) and 500–250-mb. thickness contours (dashed lines) in hundreds of feet and at intervals of 200 ft. (C) 250-mb. contours (solid lines) in hundreds of feet and at 400-ft. intervals, the 250-mb. jet stream (heavy solid lines) with arrows showing the direction of flow, and 250-mb. isotherms (dashed lines) at intervals of 5° C.

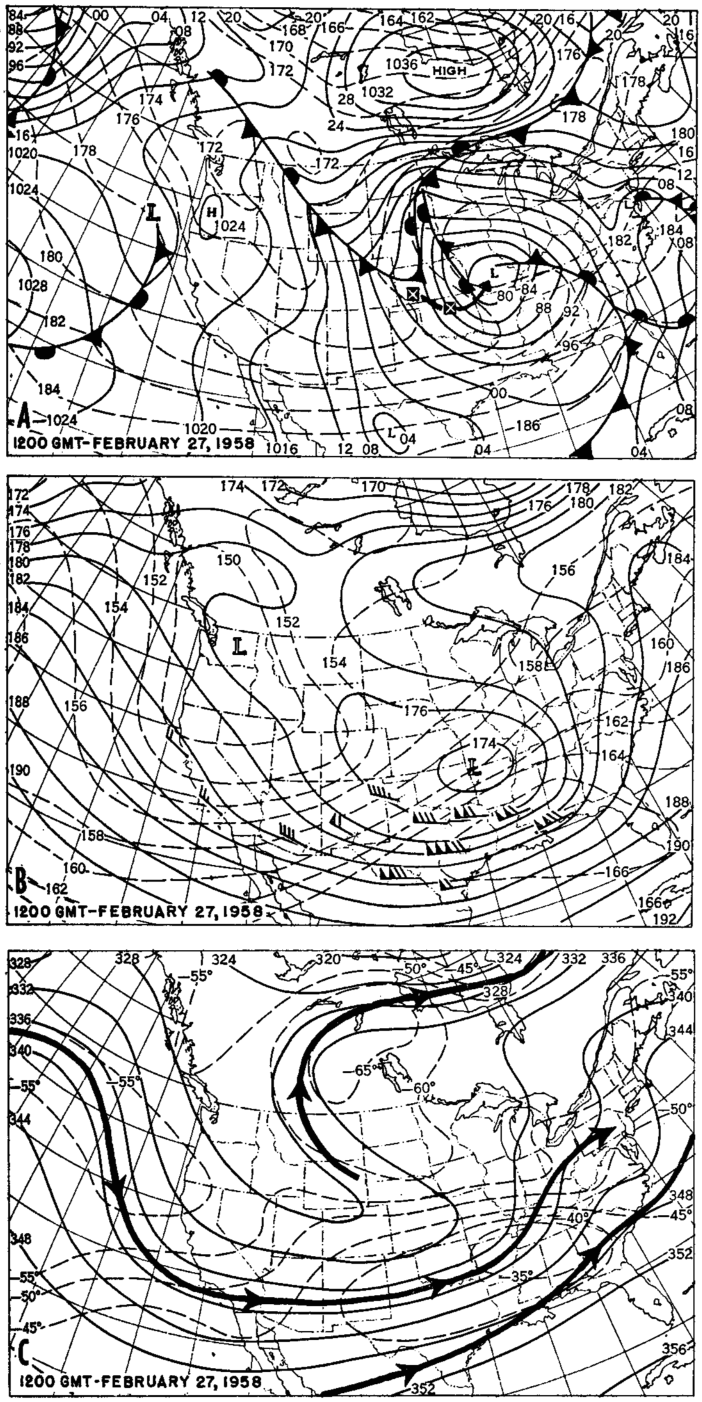

Figure 3.—1200 GMT charts, February 27, 1958. (A) Surface weather map with isobars (solid lines) at 4-mb. intervals and 1000–500-mb. thickness contours (dashed lines) in hundreds of feet and at intervals of 200 ft. (B) 500-mb. contours (solid lines) and 500–250-mb. thickness contours (dashed lines) in hundreds of feet and at intervals of 200 ft. (C) 250-mb. contours (solid lines) in hundreds of feet and at 400-ft intervals, the 250-mb. jet stream (heavy solid lines) with arrows showing the direction of flow, and 250-mb. isotherms (dashed lines) at intervals of 5° C.

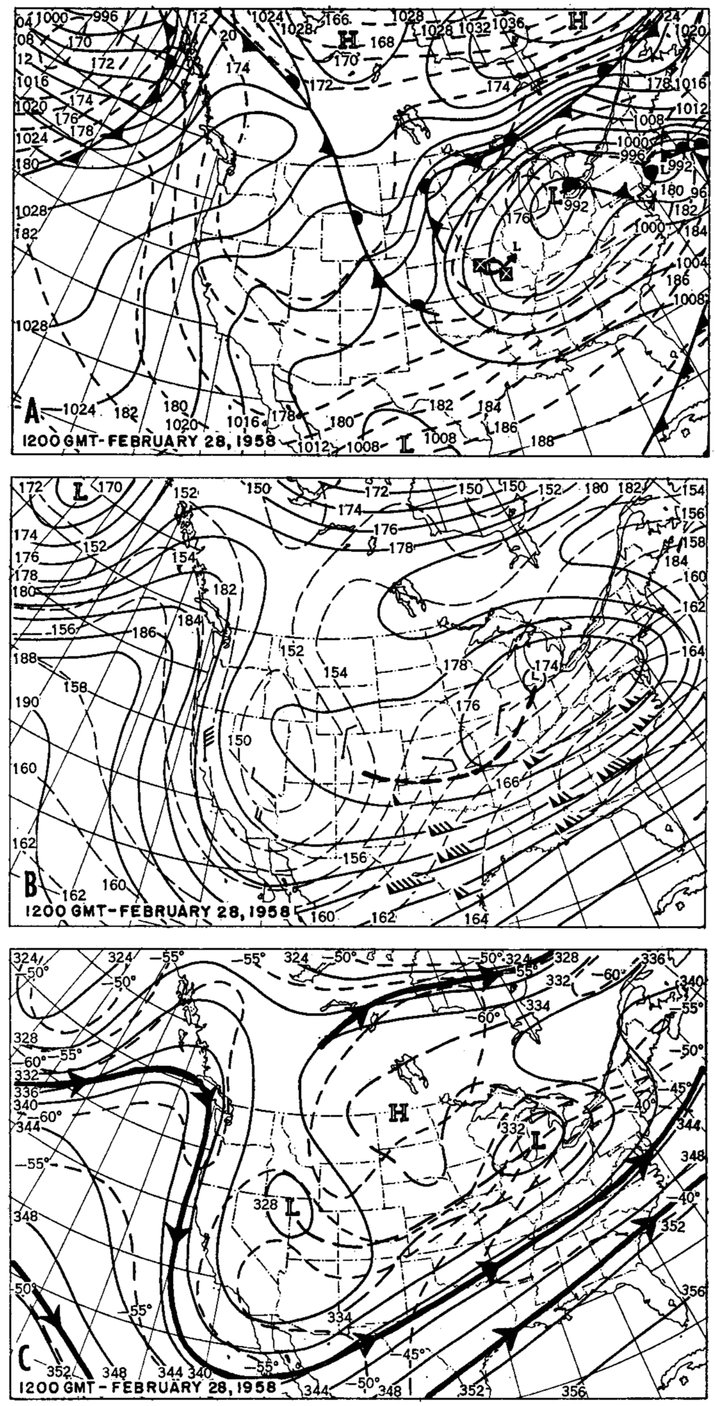

Figure 4.—1200 GMT charts, February 28, 1958. (A) Surface weather map with isobars (solid lines) at 4-mb. intervals and 1000–500-mb. thickness contours (dashed lines) in hundreds of feet and at intervals of 200 ft. (B) 500-mb. contours (solid lines) and 500–250-mb. thickness contours (dashed lines) in hundreds of feet and at intervals of 200 ft. (C) 250-mb. contours (solid lines) in hundreds of feet and at 400-ft intervals, the 250-mb. jet stream (heavy solid lines) with arrows showing the direction of flow, and 250-mb. isotherms (dashed lines) at intervals of 5° C.

stations in western Kansas, southwestern Nebraska, and eastern Colorado showed falls of about 20 mb.

The spectacular deepening of this storm over northwestern Kansas between February 25 and 26 appears to be a classic example of the influx of sustained high-speed winds toward diverging cyclonically curved contours resulting in large contour falls downstream to the left of the inertial path of the strong winds. The effect of large-scale horizontal mass divergence in the upper troposphere overcompensating the low tropospheric increase in density becomes particularly apparent in this storm.

Mass divergence, i. e., depletion of mass, produces pressure or height falls at the base of the air column. This mass divergence involves the density field as well as the velocity field, and is of primary significance in estimating pressure or height changes. In the lower levels density transport makes the most significant contribution to the pressure change [3]. In the upper levels mass divergence largely results from horizontal divergence of velocity and therefore can be determined from the wind field. Since geostrophic winds are approximately nondivergent, the divergence must be a property of wind departures from the geostrophic condition. The dependence of surface pressure changes on divergence in the upper troposphere makes the upper wind structure of primary importance in surface development. The jet stream with its strong wind shears and considerable departures from the geostrophic condition [4], must, therefore, play an important role in the formation and intensification of middle latitude cyclones.

Scherhag [5] was among the first to introduce the idea of diverging upper contours as a basis for surface developments. His rule can be stated as follows: "When cyclones develop, they do so in a 'delta' region, i. e., a region where upper contours diverge. They weaken or fill up in an entrance region where upper contours come together." Sutcliffe and Forsdyke [6] reached much this same conclusion from thermal patterns. They state that the combination of difluence of thickness lines is probably the most certain indication of cyclogenesis: "The advection set up by such pressure features tends to carry the cold trough forward, but with a weak thickness gradient ahead the systems do not readily break away from the thermal feature and the depression may deepen greatly with slow movement."

The level of maximum horizontal divergence is usually near the jet core level. For qualitatively detecting divergence, the large horizontal contrasts in wind speed as a result of the cumulative effect of the mean temperature field (thermal wind) are reflected more strongly in the higher levels. Thus, the 300-mb. or 250-mb. level would show the contrast between fast and slow wind speed zones even more markedly than the 500-mb. level.

At 1200 GMT February 25, 1958, the 500-mb. contours and the 500–250-mb. thickness (fig. 1B), the 250-mb. contours (fig. 1C), and the 1000–500-mb. thickness (fig. 1A) all showed a very flat, cyclonically divergent area or "delta" region over the Central and Southern Plains, just east of the Rockies. At this time, the sustained high speed jet, which had been moving eastward over the Pacific, was beginning to move over California. A strong contour gradient was propagated downstream to the right of these high speed winds in a manner described by Bjerknes [7]. The resulting upper height falls to the left of the propagation of the high speed winds contributed to large-scale horizontal divergence in the upper troposphere.

In view of the difficulty in measuring divergence directly from weather maps, it is more convenient to relate surface pressure changes to some quantity which is related to divergence. Vorticity is such a quantity. The vertical component of vorticity relative to the earth in any current is composed of horizontal shear within the current and a curvature effect. The curvature effect is directly proportional to the wind speed and inversely proportional to the radius of curvature of the streamline. Thus the effect of wind speed vanishes when the curvature of the streamline is zero. This may help account for the frontal system moving rapidly across the Pacific with little development under a jet of great intensity, but having small streamline curvatures and uniform, though intense, wind shears along its axis.

4. WARM AIR ALOFT AND THE JET STREAM

On February 17, 1958, an area of abnormally warm air was present in the upper troposphere over southeastern China. This was particularly apparent when the temperatures at several stations rose to the −25° to −30° C. range at 300 mb. More nearly normal temperatures for this level for this latitude are about −35° to −40° C. at this time of year. Yeh [8] has shown that the jet stream over southeastern Asia is almost invariant during the winter season near the latitude of 30° N. He shows the marked influence of the Himalayan mountain barrier in producing a strong confluence zone over eastern China. This natural jet stream was further strengthened by the intensification of the thermal gradient due to the influx of this warm upper tropospheric air from the south. The confluence of upper-level warm and cold currents and the resulting strong temperature gradient aloft are the essential features in the theory of Namias and Clapp [9] for the formation of the jet stream. Due to the fact that the change in wind with height is largely determined by the horizontal temperature gradient, it is clear that in the process of confluence there is a mechanism for producing a concentration of isotherms (or thickness lines) in a narrow zonal belt.

The strongest jet moved eastward across the Pacific mainly between latitudes 30° and 40° N. maintaining a strong temperature gradient and winds generally in excess of 150 kt. Data through this area of the Pacific are very sparse and even the few stations reporting do not consistently give all the upper air information that would be desired. However, the few reports available did give an estimate that the jet was stronger than normal at this time. This was borne out quite spectacularly by the temperature field at 300 mb. At 1200 GMT February 21, the 300-mb. temperature at Ship "V" (34° N., 164° E.) rose to −29° C. After this, it dropped steadily to −50° C. at 1200 GMT February 23. This high level warm air area was associated with the concentration of isotherms (confluence) and strong winds of the jet stream. At Midway, Lihue, and Hilo in the Hawaiian Islands the temperature rise was not as apparent probably because they were too far south, but at Ship "N" (30° N., 140° W.) the 300-mb. temperature rose from −43° C. at 0000 GMT February 22 to −30° C., at 0000 GMT February 24 after which it again fell. Stations in California were the next to show this marked high-level warming. At 1200 GMT February 23 the 300-mb. temperatures at these stations ranged from −47° to −48° C. and at 0000 GMT February 25 they were −36° to −38° C., and by 0000 GMT February 26 they were −31° to −34° C. The denser network of stations over the United States greatly increased the definition of this high tropospheric warming as it moved eastward.

Figure 1C shows a closed −40° C. isotherm at 250 mb. over northern California at 1200 GMT February 25. Corresponding to this, figure 1B shows an anticyclonic curvature of the 500–250-mb. thickness (note the 16,400-ft. thickness line) along the California coast. By 1200 GMT February 26 (fig. 2C) there was a closed −35° C. isotherm at 250 mb. over the New Mexico and western Texas area, and the anticyclonic curvature of the 500–250-mb. thickness (fig. 2B) had moved to this same area. Note too, the packing of the thickness lines from New Mexico westward. By 1200 GMT February 27 (fig. 3C) the area enclosed by the −35° C. isotherm had increased in size and extended from over Arkansas to northwestern Georgia. The anticyclonic curvature of the 500–250-mb. thickness (fig. 3B) extended over the same area, but by this time the air had become even warmer with a closed 16,600-ft. thickness contour over the northern Gulf of Mexico and southern Gulf States. Note again the packing of the thickness lines from Tennessee westward. By 1200 GMT February 28, this now familiar pattern had the −35° C. closed isotherm at 250 mb. centered over Maryland (fig. 4C) while the 500–250-mb. thickness had a corresponding anticyclonic curvature in the same area (fig. 4B) with the large closed warm 16,600-ft. thickness contour centered over the Carolinas. The packing of the thickness lines to the west is again notable. The maintenance of this high level warm area, as it moved over the central and eastern United States at a speed much slower than the winds through it, certainly must be attributed to the very strong subsidence and associated divergence.

The jet maximum continued to be very strong as it crossed the United States in association with this very strong confluence zone, with winds generally in excess of 150 kt. and near 200 kt. at many places. Figure 5 shows the successive 24-hour (1200 GMT) positions of the 150-kt. isotach at the 300-mb. level with the approximate centers of the jet maxima as the jet crossed the United States during the 4-day period February 25–28, 1958. It appears that the center of the warm air aloft preceded the jet maximum by approximately 12 hours. Even at 500 mb., westerlies averaged 60 to 70 kt. stronger than normal, as indicated by the departure from normal charts. Well below normal heights existed to the north, and near to slightly above normal heights to the south throughout the history of this jet across the Pacific and the United States.

5. ADDITIONAL FACTORS OF DEVELOPMENT

Experience shows that almost all cyclogenesis at sea level occurs in advance of an upper trough; i. e., under an area of divergence and positive vorticity advection in the upper troposphere. Since cyclogenesis at sea level requires convergence of appreciable amounts, particularly in the lower troposphere, there must be appreciable amounts of divergence in the upper troposphere to more than offset these low level effects. Petterssen, Dunn, and Means [10] formulated and tested a working hypothesis that "cyclonic development at sea level occurs when and where an area of positive vorticity advection in the upper troposphere becomes superimposed upon a frontal zone at sea level." They show that conditions favorable for large positive vorticity advection are: (a) rapid decrease in curvature of contours ahead of the trough line, (b) rapidly diverging (fanning) contours ahead of the trough line, and (c) strong winds.

As we have seen, there was an intense area of high-level divergence centered over the southern Rockies and central and southern High Plains area at 1200 GMT February 25 (figs. 1B and 1C). This is in agreement with the above hypothesis. In figure 6, the 12-hour 500-mb. height change was superimposed over the corresponding 12-hour surface pressure change for 1200 GMT February 25. In the area of northern Nevada there was already an appreciable fall of just over 600 ft. at 500 mb. The location of the large fall area to the southwest indicates a considerable increase in vorticity along the coast of California. This was tied in with the concept of positive vorticity advection as the pressure gradient had increased and the higher speed winds were moving into the trough area. Note that the surface zero isallobar through Nevada intersected the fall of 600 ft. at 500 mb. Thus, the thickness between the surface and 500 mb. decreased by 600 ft. indicating the strong baroclinicity at this time. From a check back to the 0000 GMT maps for February 25 to get a 12-hour estimate of the indicated cold advection, it was found that advection alone could account, at most, for approximately 200 ft. of this fall. The remaining 400 ft. of the decrease in thickness was necessarily a result of strong vertical motions that were becoming significant at this time. Note also, in figure 6, that the largest surface fall area of −20 mb. was located just north of western North Dakota and an extensive

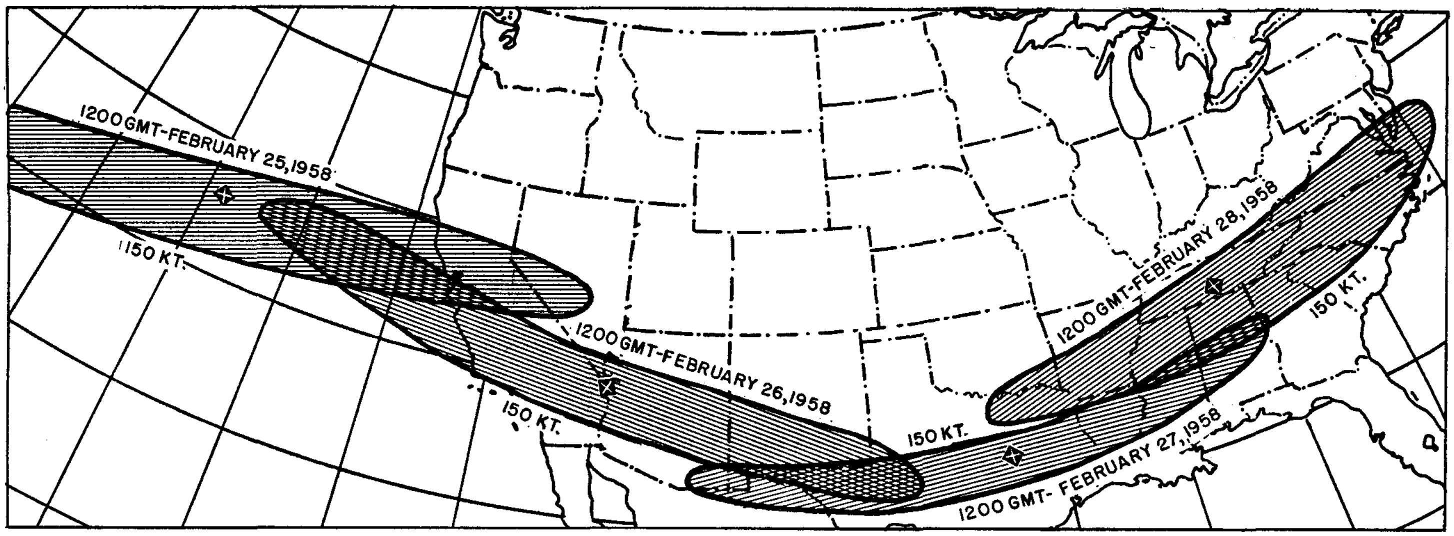

FIGURE 5.—Successive 24-hour (1200 GMT) positions of 150-kt. isotach at the 300-mb. level, February 25–28, 1958. The approximate centers of the jet maximum are denoted by X.

fall area extended southwestward from Wyoming. Scherhag's [5] rule for displacement and intensity of isallobaric areas is as follows: "If the isallobars are moving toward diverging contours aloft (delta region) the intensity of the fall area would be increased or rise area decreased."

Twenty-four hours later, at 1200 GMT February 26, the 12-hour 500-mb. height change (fig. 7) showed a 200-ft. fall area over the entire central portion of the United States with a fall area of more than 400 ft. centered in eastern New Mexico. Again, the position of the fall area at 500 mb. indicated the increase in vorticity into eastern New Mexico with the increase of gradients and cyclonic curvature (figs. 2B and 2C). At this same time the 12-hour surface pressure change had a fall area of 16 mb. centered near Ponca City, Okla. Over New Mexico and southern Colorado the surface zero isallobar under the 400-ft. fall area at 500 mb. showed a decrease in the thickness of 400 ft. indicating the continuing baroclinicity at this time. Also, the 1000–500-mb. thickness lines (fig. 2A) were perpendicular to the surface isobars indicating considerable cold advection from eastern New Mexico westward. To the east of the surface fall center and within the area of 200-ft. falls at 500 mb., further sea level development was also indicated because the upper falls were not compensated by low thickness advection or by adiabatic lifting in the convergence area ahead of the trough. In this area, the surface and 500-mb. levels each appeared to be falling approximately the same amount indicating that the contribution to development must have been a decrease of mass above 500 mb. Slightly more development did occur during the next 24 hours as the Low moved southeastward through northeastern Oklahoma then recurved toward the northeast.

At 1200 GMT February 27 (fig. 3A) the Low was located just south of Columbia, Mo. At this time the area of strongest cold air advection appeared well to the south, along the northern Gulf of Mexico westward through Texas. Since the area was under a very strong high level flow it was displaced rapidly eastward. The thickness field around the Low appears to have been an exaggerated form of the sinusoidal or "S" pattern after Sutcliffe and Forsdyke [6]. They state, "The reverse thermal gradient over the cyclonic region is not in harmony with wave-like thermal steering and the situation is liable to evolve further with little movement." Actually, the Low reached its maximum intensity at 1500 GMT February 27 near Columbia, Mo. where a sea level pressure of 973 mb. was reported. During this 24-hour period the Low looped through west-central Missouri, and by 1200 GMT February 28 (fig. 4A) it was a filling Low located in southwestern Illinois with almost no thickness gradient around it.

6. DIVERGENCE AND SUBSIDENCE

With rapidly deepening Lows, the change in mass in the stratosphere and upper troposphere contributes more to the local surface pressure change than does the lower tropospheric change in density. Warming is frequently observed in the stratosphere over deepening surface Lows pointing to subsidence in the lower stratosphere, or above the level of maximum horizontal divergence. This warming is accompanied by lowering heights of the constant pressure surfaces in the lower stratosphere, indicating a decrease in mass at high levels as a result of subsidence uncompensated for by inflow above. Vederman [11] studied the density and mass changes in columns of air moving with 25 rapidly deepening Lows east of the Rockies, all of which deepened 10 mb. or more. He showed that the air column over the moving center became progressively cooler and denser in the lower half of the atmosphere as the storm deepened, and that the removal of mass necessary to produce the lowering surface pressure had a preferred region in the top one-third of the atmosphere, as shown by the marked warming he observed between 300 and 100 mb.

A study was made of the vertical structure of the Low from the time of its formation in northwestern Kansas until it was near Columbia, Mo. Fortunately, each 12-hour position of the Low center was remarkably close to a radiosonde station (first Denver, Colo., then Dodge City, Kans., then Oklahoma City, Okla. and finally Columbia, Mo.). The results followed very closely those obtained by Vederman. The Oklahoma City raob (fig. 8) was very representative of the conditions from which our conclusions were reached. This raob is of further interest because Oklahoma City reported a record low sea level pressure reading of 975.2 mb. at 2133 GMT February 26, less than 3 hours before raob release time.

At 0000 GMT February 26 Oklahoma City reported a sea level pressure of 1000 mb., and at 0000 GMT February 27 a reading of 981 mb., or a net fall of 19 mb. during the 24-hour period. This was equivalent to a 520-ft. fall of the height of the 1000-mb. surface. Figure 8 shows the soundings at Oklahoma City at 0000 GMT on both of these days. The layers below approximately 400 mb. cooled while the layers above warmed considerably. This cooling, or increase in density amounted to a decrease in thickness of 430 ft. between the surface and 400 mb. At the same time, the warming showed an increase of 820 ft. in thickness between 400 mb. and 150 mb. Thus the total thickness between the surface and 150 mb. increased by 390 ft. The 150-mb. level actually lowered by 130 ft. This 130 ft. of lowering plus the 390-ft. increase in thickness equals the 520-ft. fall in height recorded at the surface. The major contribution to the fall in pressure at the surface thus came from the layer of warming above 400 mb. and particularly the layer of maximum horizontal divergence. In the Oklahoma City sounding, the temperature curve was almost isothermal from 400 mb. to 150 mb. indicating that considerable subsidence must have occurred. This warming by subsidence caused by the divergence field was noted at all of the raob stations in the path of the Low.

The high-level warming was also very evident to the south of the Low, as has been shown, along the path of the very strong jet. The level of warming seemed to appear at successively lower levels southward through the jet area. For instance, at 1200 GMT February 27 at Fort Worth, Tex. the maximum increase in temperature occurred in the layer between approximately 460 mb. and 260 mb. At the same time at Bryan, Tex. the maximum increase was in the layer between about 540 mb. and 270 mb. The jet maximum at the 500-mb. level appeared over the Bryan area (fig. 3B), while at the 250-mb. level (fig. 3C) it was through northern Texas, and at the 300-mb. level (fig. 5) near the Fort Worth area. At this time Bryan reported a wind of 170 kt. at 18,000 ft., 190 kt. at 20,000 ft., and 117 kt. at 22,000 ft. The implied excessive thermal wind between the 20,000-ft. and 22,000-ft. levels and also the fact that this was the highest reported level gives rise to some doubt as to the validity of this report. Why such a strong wind should exist at this low level would require a study in itself. However, it does at least show that the subsidence effect must have been considerable.

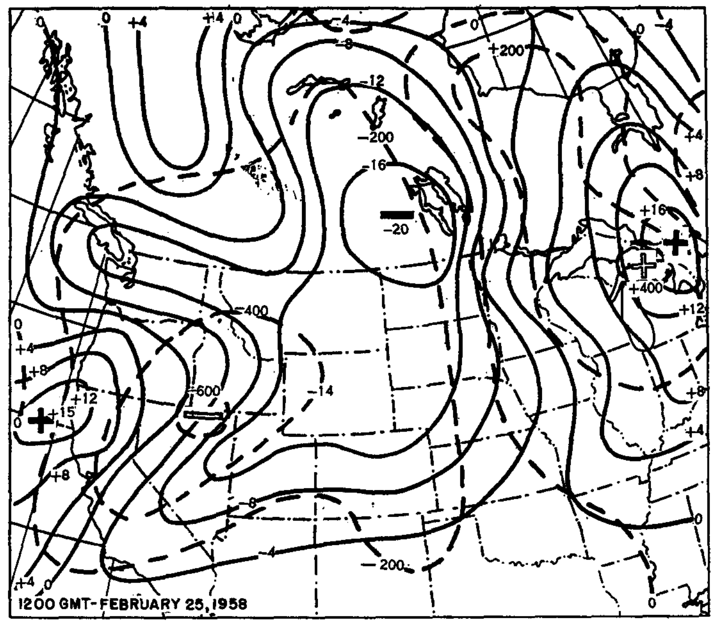

FIGURE 6.—12-hour surface isallobars (solid lines) at 4-mb. intervals and 12-hour 500-mb. height change (dashed lines) in feet for the period 0000 GMT to 1200 GMT February 25, 1958. Rise and fall areas are indicated by plus or minus signs.

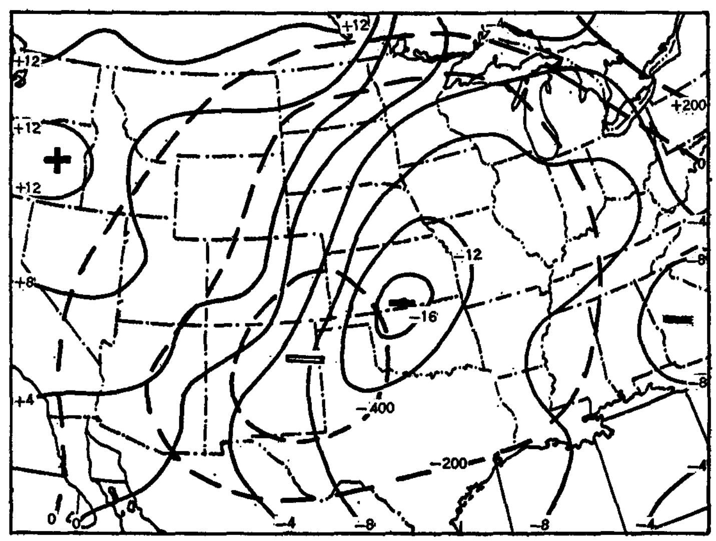

FIGURE 7.—12-hour surface isallobars (solid lines) at 4-mb. intervals and 12-hour 500-mb. height change (dashed lines) in feet and for the period 0000 GMT to 1200 GMT February 26, 1958. Rise and fall areas are indicated by plus or minus signs.

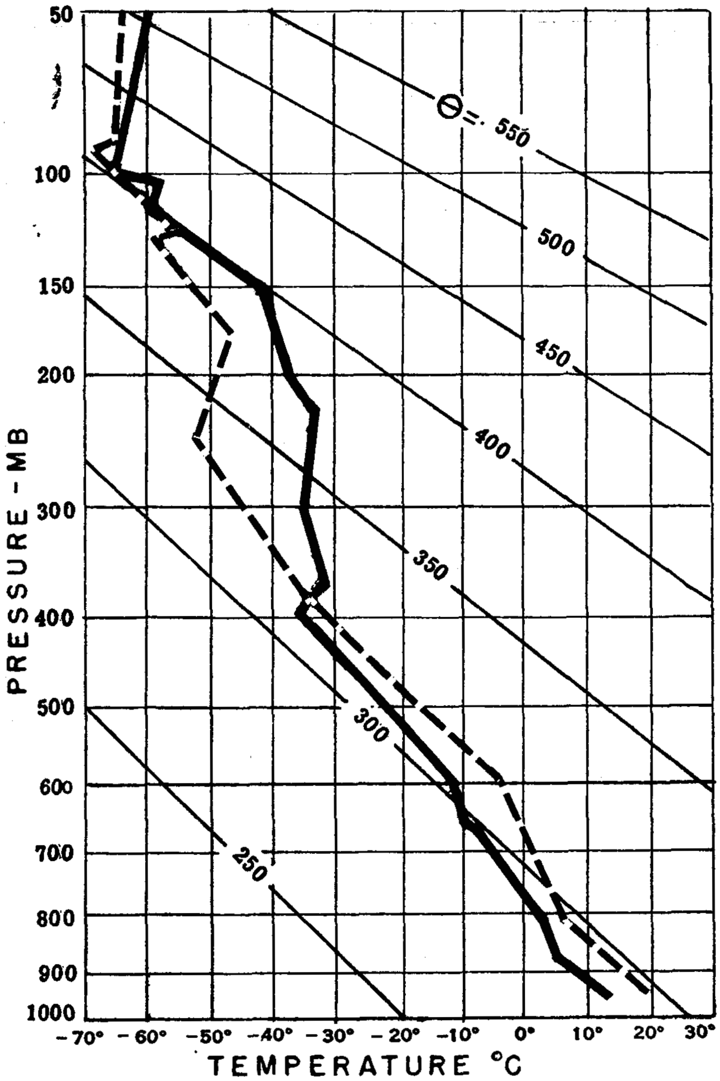

FIGURE 8.—Oklahoma City raobs for 0000 GMT February 26, 1958 (dashed curve) and for 0000 GMT February 27, 1958 (solid curve).

The temperature field above the jet at 500 mb. seemed to reverse; at 250 mb. (note temperature field in fig. 3C) and also at 300 mb., it was actually slightly warmer through northern Texas and Arkansas than in southern Texas and along the Gulf Coast. This may help account for the northward displacement of the 300- and 250-mb. jets from the 500-mb. position.

7. JET PROPAGATION ASSOCIATED WITH STORM DEVELOPMENT

The high-speed winds (at 500 mb. and above) (figs. 1B and C) that entered the California area were supergradient as they encountered the weaker pressure gradient area over the southern Rockies and central and southern High Plains. Their deflection to the right toward higher pressure and consequent deceleration tended to slow up the southeastward progress of the isotach maximum which in this case tended to move at about 40 to 45 kt. The high-speed winds could not propagate southeastward until the pressure to the north had fallen sufficiently to strengthen the contour gradient farther south enough to balance the Coriolis and centrifugal forces of the high-speed parcels. By 1200 GMT February 26 (figs. 2B, 2C, and 5) the isotach maximum as implied by the upper-level contours had penetrated to western Arizona. The upper trough continued to increase in amplitude until the contour gradient was strong enough to balance the Coriolis and centrifugal forces of the high-speed air crossing the trough line. This condition was reached at about 1200 GMT February 27 (figs. 3B and C). As the ridge to the east had diverging contours with a weaker gradient the isotach maximum moved slightly more slowly. When the height falls strengthened the contour gradient east of the trough and to the left of the isotach maximum sufficiently to balance the high speed winds emerging from the southern part of the trough, the isotach maximum was propagated northeastward with undiminished speed and by 1200 GMT February 28 (figs. 4B, 4C, and 5) was located in the area of southeastern Tennessee.

The propagation of the isotach maximum was related to the following developments: While the maximum winds were on the west side of the upper trough (figs. 1, 2, and 5) the trough deepened, the surface Low deepened, and the high-level height falls moved south of east. When the maximum winds were in the southern part of the upper trough (figs. 3, 5) the height falls moved eastward and the trough did not change much in amplitude. At this time, 1500 GMT February 27, the surface Low reached its maximum development with a central pressure of 973 mb. near Columbia, Mo. When the maximum winds penetrated to the east side of the trough, the trough began to fill and the surface Low looped and also filled. By 1200 GMT February 28, the high-level height falls had moved northeastward; on the surface map the filling Low was located in Illinois with redevelopment along the east coast (figs. 4, 5).

8. SUMMARY

The cyclogenesis and movement of this storm in the Midwest could be called a "classic" in its pattern of development. A much above normal high-speed jet moved into an area of diverging cyclonically curved contours. The resulting strong divergence in the upper troposphere was apparently the most important effect which caused the marked height falls aloft and the record-breaking sea level pressure readings at the surface. Vigorous vertical motions were also created as a result of the strong horizontal divergence. Vorticity advection and the jet maximum propagation also were closely associated with the deepening, movement, and filling of the storm at the surface.

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